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AN INTRODUCTION TO FUEL CELLS

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These paragraphs are intended to acquaint the reader with the general properties of fuel cells. The development of this field is so rapid that a status report would become out-dated very quickly. The scientific and engineering literature should be consulted for current information about specific types of cells and about complete systems.

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Definitions

The fuel cell is the only known device that can continuously convert chemical energy directly to electrical energy.

This definition is broader than, for example, that given by Justi (E. Justi and A. Winsel, "Kalte Verbrennung -- Fuel Cells", F. Steiner Verlag, Wiesbaden (Germany), 1962, p. 4): "A fuel cell is a device in which free energy, liberated upon oxidation of a conventional fuel, is obtained directly as electrical energy." Definitions that stress "oxidation" and "conventional fuels" are intended to limit application of the term "fuel cell"; hence they necessitate coining definitions for other electrochemical systems that can operate continuously. An all-inclusive definition is preferable for our purposes, however.

The distinction between fuel cells and other electrochemical systems, i.e., conventional electrochemical cells and batteries, will tend to diminish as more and more hybrid systems are devised. Hydrogen and oxygen, e.g., are widely considered to be conventional fuel and oxidant, respectively. An electrochemical device that uses and regenerates these chemicals in a

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closed cycle -- with a net input of energy, of course -- is a fuel-cell battery as well as a gas-storage battery. We shall therefore use the capability of continuous operation as the only criterion for distinguishing between "batteries", as the conventional devices are loosely called, and "fuel cells". Following popular usage, we shall sometimes speak of fuel cells even when fuel-cell batteries and systems are meant.

A more precise definition can now be formulated:

A fuel cell is an electrochemical device in which most of the free energy of reaction of one or more chemical species can be transformed directly into electrical energy. Reactants are added on demand, and products are removed as required.

Thus, the only difference between a battery and a fuel cell is that the former, being self-contained, has a limited useful life before being discarded or recharged; the latter should operate for an indefinite time, at least in theory, as long as the proper flow of chemicals is maintained.

A fuel cell per se is a device for converting energy. It can also be looked upon as a chemical reactor that yields electricity as one of its byproducts. A fuel-cell system, including reactants, is an energy-storage conversion device.

The main constituents of a fuel cell are the case, negative electrode (anode), positive electrode (cathode), electrolyte, inlets for the reactants, and outlets for the products. The electrodes may contain catalysts for speeding up the desired reactions. Membranes may be inserted to impede unwanted diffusion of species. This deceptively simple-looking device can be simplified even further by replacing one reactant with a

vacuum, although calculations made by Westinghouse scientists indicate that such concentration cells would be inferior to conventional fuel cells, except under unusual conditions.

In practice, it is far from a simple matter to maintain the components of the fuel cell invariant, to obtain high reactivity of reactants, and to operate at high efficiency.

Classifications

Electrochemical equipment may be used in two ways: Some batteries can only be discharged once, others can be recharged repeatedly. The former are primary, the latter secondary devices. Similarly, there are primary fuel cells, through which the reactants pass only once; and secondary or regenerative fuel cells, the products from which are regenerated so that reactants can be re-used many times. Fuel-cell reactants can be regenerated by electricity, heat, light, and radioactivity. Of these energy sources, the last two have been too inefficient thus far to merit further consideration at this time. In principle, even petroleum could be resynthesized and air could be reconstituted from the products of a petroleum-air fuel cell. For obvious reasons, regenerative fuel cells are operated with simpler, purer, and sometimes more expensive chemicals. The cost of chemicals is less important in this case, because they are re-usable.

Except for the additional reprocessing step, primary and secondary fuel cells operate in the same manner. We may thus ignore this distinction for further classification, remembering only that each of the following kinds of fuel cells can be used as a primary or a secondary energy conversion device.

The temperature range in which a fuel cell operates furnishes a useful criterion for classification. Even though the boundaries are arbitrary and not sharply defined, one may distinguish among low-, intermediate-, high-, and very high-temperature fuel cells. Low temperature ranges up to about 150°C, intermediate to 400°, high to 800°, and very high above 800°C.

A "high-temperature" hybrid between a (regenerative) fuel cell and a thermoelectric device, the thermogalvanic cell or simply thermocell, will not be considered here, since it is more properly considered to be a liquid thermoelectric device, i.e., a means for converting heat to electricity. Similarly, biochemical fuel cells are not included in this discussion.

Within each of the first three temperature ranges, at least, one can again subdivide fuel cells by the type of electrolyte that is used. This may be a free liquid, a restrained liquid (contained in a membrane, mat, or matrix), a paste, or a solid or pseudo-solid. The very high-temperature fuel cell has been operated only with a solid electrolyte.

Finally, depending upon whether the reactants are gaseous, liquid, or solid, one uses porous or true diffusion-type, inert non-porous, or consumable electrodes.

Table 1 summarizes the criteria used for classifying fuel cells.

Properties

The most important reason for the widespread commercial and governmental interest in fuel cells is implied in the definitions given above. By converting chemical to electrical energy directly, the primary fuel cell is not subject to the theoretical limitation that applies to all heat engines -- the Carnot-cycle efficiency

$$(T_1 - T_2) / T_2$$

Table 1. - Classification of Fuel Cells

Mode of Operation

Primary

Secondary

Temperature Range

Low (up to 150°C)

Intermediate (150°-400°C)

High (400°-800°C)

Very High (above 800°C)

Electrolyte

Free Liquid

Restrained Liquid

Paste

Solid

Electrode or Reactant

(Porous) Diffusion ↔ Gaseous

Non-porous ↗↔ Liquid

Consumable ↔ Solid

(Combinations and mixtures)

where T_1 is the (higher) inlet temperature and T_2 the (lower) exhaust temperature. For practical purposes, this amounts to about 0.5 to 0.6 or 50 to 60%. Modern commercial power plants have attained a little over 40% efficiency.

The theoretical limit for the efficiency of fuel cells is the ideal efficiency,

$$\Delta F/\Delta H,$$

the ratio of the change in free energy to heat content of the chemical reaction. Though this might amount to more than 80%, practical fuel cells are expected to operate at 40 to 65% efficiency. Higher efficiencies are unlikely because the voltage drops as more current is drawn from a fuel cell, and a compromise must be made between efficiency and power (=voltage x current) obtained per cell.

The efficiency of small thermal power plants is far from that of a modern station for generating electricity. Thus, a gasoline engine might have an efficiency of 10-25%. The fuel cell is not subject to such scaling limitations. Its efficiency is independent of size, but system efficiency will be affected by the possible need for parasitic power, e.g., to drive pumps; and by the efficiency of DC-to-DC converters or DC-to-AC inverters, if required.

Another advantage over rotating machinery is that, when used at part load, the fuel cell has a lower relative fuel consumption than at full load; engines, on the other hand, consume relatively more fuel under such conditions. Thus, fuel cells will be particularly advantageous because of

their higher efficiency when power profiles vary widely, as for frequent stop-and-go or on-off cycles.

Unlike rotating machinery, the fuel cell proper has no moving mechanical parts. Although most fuel-cell systems of any but the smallest size will need pumps and valves, they should run more silently and require less maintenance than do conventional generators. Furthermore, a modular approach is feasible, minimizing the need for standby equipment and facilitating repairs.

Fuel cells using conventional fuels and air are expected to yield mainly carbon dioxide and water as reaction products; nitrogen and other inert constituents of the air will be ejected unchanged. Such innocuous products are a necessity for power plants operating in closed areas, such as warehouses and underground mines without forced air circulation. Although they may emit some "unburned" reaction intermediates, fuel cells could contribute toward solving the problem of air pollution, caused by exhaust fumes in urban areas, by minimizing the amount of noxious products and releasing them in more highly concentrated streams that are purified more easily.

Operation of fuel cells at low temperatures is highly desirable for quickly starting motive power plants. Low-temperature reactants are available. For the present, however, the temperature of operability and the cost of the fuel appear to have an inverse relationship, i.e., the lower the fuel cost the higher the operating temperature. Nevertheless, a large market for, say, methanol would undoubtedly result in a marked reduction of its cost. Use of an auxiliary heater or other power source for quick start-up is a possibility.

Multifuel capability offers another or a complementary approach to the problem of fast-starting fuel cells. All fuel cells designed for "conventional" fuels operate better on hydrogen, hydrazine, or methanol. Multifuel capability of some fuel cells in all temperature ranges has already been demonstrated. As might be expected, their versatility increases at higher temperatures.

Power densities can not yet compete with those of engines, considering that a gasoline engine can develop about 12 kw/ft³ or more, as compared with perhaps 1-3 kw/ft³ for present fuel cells. These numbers are important mostly for motive power, of course. But they must be used with caution, and that for various reasons: An internal combustion engine requires gears and a drive shaft to get the power to the wheels. A fuel-cell battery requires controls, pumps, and plumbing. More important, a fuel-cell battery in a car, truck, locomotive, or ship operates one or more electric motors. In this respect, fuel cells are at a decided disadvantage as compared with combustion engines. High-performance electrodes, now under development, promise some improvement.

Improvements are also needed in weight, volume, and cost of DC motors. On the other hand, the DC motor has a high starting torque, thus offering some saving in horse-power requirements; furthermore, dynamic braking might be provided. Solid-state control devices, exemplified by pulse-width modulation circuits, will eliminate much waste of power in start-stop operations and protect equipment from overloads.

Costs of fuel cells are still far from being competitive with the \$3/kw for mass-produced engines. Production costs will drop sharply when demand warrants mass production. Investment costs of low-temperature fuel cells, particularly, must be reduced by minimizing the need for platinum and

palladium or by developing non-noble catalysts. If reformers (see below) are to be used commercially, palladium-silver alloy diffusers are too expensive, and the supply of palladium for large-scale use would probably be inadequate, anyhow. Maintenance costs are still completely unknown.

Because fuel cells typically produce low-voltage, high-amperage DC in conventional operation, it has been assumed that expensive equipment for DC-to-AC inversion will be required for certain purposes. Conceivably, however, ingenious electrical engineering approaches, such as interruption and phasing of outputs from several fuel-cell units, might bypass the need for conventional inversion equipment. Quite generally, better engineering of fuel cells and application of scientific principles that have been thoroughly explored in other areas may be expected to make contributions that are just as valuable as research in the fuel-cell area proper.

Systems

Very little is known about the longevity and reliability of complete fuel-cell systems. To be sure, some companies have thousands of hours of test time on single cells and small assemblies of cells. But a full-scale, fully engineered power plant is an entirely different matter.

Statistics of upscaling from small to large cells and especially from single cells to usable fuel batteries are virtually non-existent. At this stage, quality control for the components of small cells is difficult enough; the uniformity of electrodes and separators (or membranes) for large cells poses much more severe problems. Rates and modes of cell failure in batteries are likely to be quite different from those of single cells; even these are still unknown in many cases. Systems-engineering and life-testing of full-scale batteries have barely begun.

In some cases, optimum operating conditions may not be precisely known; or if known, have not been achieved for long periods; or if achieved, have not been maintained by optimum control methods. Much valuable information of this kind is being accumulated in connection with the two fuel-cell systems for NASA's Gemini and Apollo projects. Nevertheless, even these data may not be directly applicable to most earthbound uses, considering that the systems will be supplied with very pure hydrogen and oxygen and will have to endure only a few weeks of operation.

Several efforts are now underway on reforming or cracking "fuels" -- petroleum fractions, alcohols, ammonia -- to obtain more or less pure hydrogen. The objective is to bypass the need for any but hydrogen-air or hydrogen-oxygen fuel cells by combining, say, a reformer with a fuel cell. For greatest efficiency, the fuel cell should operate on the reformed gas at the temperature at which it becomes available and should generate just enough heat to supply the amount needed for reforming. But other considerations may make low-temperature fuel cells more attractive. Hence all fuel cells are potential consumers of carbonaceous fuels -- at a price. This price may include not only loss of some efficiency but also further treatment, e.g., cleaning and shifting, of gases.

Commercial Uses

Since fuel cells are devices for producing electricity, one must ask how their low-voltage, high-current product can best be used. Four obvious applications are central power, industrial power, individual home power, and motive power.

Most authorities are pessimistic about large-scale central power, pointing out that nuclear power is likely to be lower in cost by the time fuel cells are ready for this purpose.

Industrial power, generated at the site of use, is another matter. Metallurgical needs, e.g., are for just the kind of DC that is produced by fuel cells. Remote pumping stations for natural gas, use of byproduct hydrogen, and cathodic pipeline protection have been considered, also.

The Institute of Gas Technology, with support from the American Gas Association, has studied the potentials of fuel cells for individual home use. Von Fredersdorff indicated the importance of fixed costs for consumer markets: He showed the need for storage batteries in a domestic power pack, to cope with peak loads, and also assumed availability of DC-AC inversion equipment. Under optimum conditions, he arrived at a minimum payout time of 10 years for a home installation, when fuel-cell investment costs are \$300/kw.

Fuel cells for motive power will make possible individual electric motors for each wheel and distribution of the power package over several parts of the vehicle.

In conclusion, the commercial potentialities for fuel cells are large. How quickly and how completely they will be realized depends on the speed and ingenuity with which major problems can be overcome that now prevent fuel cells from competing with conventional power plants.

References to Recent Reports on Fuel Cells

1. Information on fuel cells for demonstration, exhibits, and reports:
 - a. "How to make a demonstration fuel cell" (Alcohol/air cell)
available from Esso Research and Engineering Co.
P. O. Box 45
Linden, N.J.
 - b. U.S. Patent 3,163,560 (December 1964) (Alcohol/peroxide cell)
"Nontoxic liquid fuel cell", P.G. Grimes and J. G. Seibold
for further information, contact Allis-Chalmers Mfg. Co.
1100 So. 70th St.
Milwaukee 1, Wisconsin
 - c. "Air depolarized batteries", E. A. Schumacher (Various low-temperature
cells)
for further information, contact Union Carbide Corp.
P.O. Box 6116
Cleveland 1, Ohio
 - d. Concerning the Gemini fuel cell, contact General Electric Co.
950 Western Ave.
West Lynn, Mass.
 - e. Concerning the Apollo fuel cell, contact Pratt & Whitney Aircraft Co.
400 Main Street
E. Hartford 8, Conn.
 - f. Concerning an indirect coal-burning fuel cell, contact
Westinghouse Research and Development Center
Pittsburgh, Pa., 15235
 - g. Concerning molten-carbonate fuel cells, contact
Texas Instruments, Inc.
P.O. Box 5936
Dallas 22, Texas

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Institute of Gas Technology
3424 S. State St.
Chicago, Ill., 60616

Above are some of the many organizations active in fuel-cell research and development.

2. Literature on fuel cells (mostly recent publications).

a. The following status reports can be bought from the

Clearinghouse for Federal Scientific & Technical Information
U.S. Department of Commerce
Springfield, Va., 22151:

Status Report on Fuel Cells,	AD-219389,	\$1.25	(1959)
Second " " " "	AD-253705,	\$0.75	(1960)
Third " " " "	AD-286686,	\$2.75	(1962)
Fourth " " " "	AD-417392,	\$2.00	(1963)
Fifth " " " "	AD-620114,	\$6.00	(1965)

- b. "Fuel Cells", 1963 (14 articles, 98 pages, \$7.50) from American Institute of Chemical Engineers, 345 E 47th St., New York 17, N.Y.
- c. "Fuel Cell Systems", 1965, 1965 (25 articles, 360 pages, \$8.00) from American Chemical Society, 1155-16th St., N.W., Washington, D.C. 20036.
- d. "Engineering Developments in Energy Conversion", 1965 (includes 6 fuel-cell papers) from American Society of Mechanical Engineers, 345 E 47th St., New York 17, N.Y.
- e. "Proceedings of 19th Annual Power Sources Conference", 1965 (includes 16 fuel-cell papers) from PSC Publications Committee, P.O. Box 891, Red Bank, N.J., 07701.
- f. "Space Power Systems", M. L. Yaffee, in Aviation Week, vol. 80, Numbers 21-24, 1964.
- g. "Fuel Cells", R. J. Jasinski and T. G. Kirkland, in Mechanical Engineering, ~~September~~ *March* 1964.
- h. "The 4 W's of Fuel Cells", E. M. Cohn, in Mining Engineering, September 1964.

Scientific and technologic journals, especially from about 1961 onward, carry many specialized fuel cell papers. Newer editions of encyclopedias also review the subject. Scientific and technical societies have national and international meetings devoted to this topic. Several texts are available in English and German.